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PERSONNEL SUPPORTED

The following personnel were supported by this grant:

Kanicki, Jerzy	Professor of EECS and PI	1/2 summer month, July 2001	
Kim, Joohan	Research Fellow, Ph.D.	6 months	50 %
Badano, Aldo	Research Fellow, Ph.D.	6 months	50 %
Martin, Sandrine	Research Fellow, Ph.D.	5 months	30 %

PUBLICATION LIST

The following papers have been published during this project:

1. "Color and Contrast Perception in Monochrome Medical Imaging Flat-Panel Displays," A. Badano and J. Kanicki, Proc. SPIE, vol. 4324, p. 1-7, 2001.

PRESENTATION LIST

The following presentations have resulted from this work:

1. "Color and Contrast Perception in Monochrome Medical Imaging Flat-Panel Displays," A. Badano and J. Kanicki, Medical Imaging 2001, February 21-22, 2001, San Diego, CA.

2. "Optimal Color for Supra-threshold and Threshold Contrast Perception," A. Badano, J. Kim and J. Kanicki, Medical Imaging Perception Conf. IX, September 20-23, 2001, Warrenton, VA.

BUDGET

Project period award: $75,750.

The major part of the budget was used to support people involved in this project. The Sony 800 TFT monitor and high gain Si detector, used in this work, were purchased during this project. The travel expenses for one person to attend national meeting was covered by this budget.

GOAL of STUDY

Mammographic films are monochrome displays with an excellent image quality, It is traditionally understood that the display of digital images in gray scale monochrome mode is the best suited for radiological imaging. Today the most color present in a radiographic film is dye (generally blue) in film base added to reduce eyestrain for the interpreting radiologist. The photopic response of the human eye is maximized for a photon wavelength of about 500 nm and decreases for higher and lower wavelengths. With the rapid development of digital image acquisition and displays systems there has arisen the possibility of creating purely color-scale radiographic images. Especially this is a very desirable for new flat-panel display technologies, such as active-matrix liquid crystal display (AM-LCD) or active-matrix organic light-emitting display. The realization of gray scale monochrome display for these technologies is not easily achievable at a low manufacturing cost. In addition, the signal acquired by a mammography flat panel detector can contain up to 12 bits of image data. It is known that the human eye cannot discern between more than 10 bits of data in a monochrome mode. Therefore, part of the information acquired by the X-ray digital detector is lost.

The goal of this project was to investigate the effect of monochrome display color on the detectability of breast abnormalities, and to develop and implement color-coding schemes, available to the user on-demand that will make use of the additional image data information. We think that the color display is capable of increased dynamic range and color radiography may have a lot of potential in practical clinical applications.

SUMMARY of RESULTS

It should be recognized that the initial goal of this work was extremely ambitious. During one year project we were able to demonstrate the following:

- Blue and green scales resulted in higher perceived contrast above the threshold.
- Contrast threshold for the saturated bleu and green, and unsaturated green scales are lower than unsaturated blue and monochrome gray scale.
- The smallest contrast threshold was obtained for unsaturated green scale.

During this project we were not able to:

- Implement color-coding schemes in AM-LCDs.
- Investigate the influence of monochrome display color on the detectability of breast abnormalities.

SUMMARY of the PROGRESS

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This project was divided in two phases. In first phase we have analyzed the color and contrast perception in the active-matrix liquid crystal display (AM-LCD). The obtained results were used to design phase II of this project. In later phase we research on contrast threshold of different colors in AM-LCD.

<u>Phase I.</u> COLOR AND CONTRAST PERCEPTION IN MONOCHROME MEDICAL IMAGING FLAT-PANEL DISPLAYS

RATIONALE

Mammographic films are monochrome displays with excellent image quality. It is traditionally understood that the display of digital images in monochrome mode (either with clear base films or with blue tint) is the best suited for radiological imaging.

However, this contention has not been proved so far. The maximum photopic response of the human eye is for a photon wavelength of about 500 nm and it decreases for higher and lower wavelengths. Also the realization of a black and white monochrome mode is not always possible at low manufacturing cost for new flat-panel display technologies, such as active-matrix liquid crystal display (AM-LCD) or active-matrix organic light-emitting display (AM-OLED). It is our goal in this project to investigate if comparable breast cancer detection performance can be achieved using other monochrome color modes (for example green or orange colors).

In addition, the signal acquired by a digital mammography flat panel X-ray detector can contain up to 12 bits of image data that depicts the transmission of X-rays through the breast. After digital transformation of the image data, a luminance map is formed within an electronic display device used for soft-copy reading.

The maximum bit-depth of current flat panel display system is 10 bit or less. It is known that the human eye cannot discern between more than 10 bits of data in a monochrome mode. Consequently, part of the information acquired by the digital X-ray detector is lost, and the observer has access to a limited portion of the complete set of information that has been collected regarding the breast. In other radiological modalities, color enhancement or color coding is being used successfully (i.e., flow Doppler ultra-sonography).

This study aims at investigating the effect of display color and color coding of the bit depth and abnormalities on diagnostic performance of soft-copy digital mammography.

OBJECTIVES

In this work, we address the following question: does observer preference or increased sensitivity to a particular color scale influence its performance in visual detection tasks defining an ideally colored gray-scale? This study aims at understanding the effect of the color of monochrome presentations on the perception of contrast by the human vision and ultimately on diagnostic performance. In this work, we report on the effect of the monochromatic scale color on the perception of supra-threshold contrast using human observers. We constrained our study to luminance-based achromatic contrast perception by using colored monochromatic scales having different color coordinates at the state of maximum luminance from a common black state. No color contrast is therefore present in the patterns. In a previous study, the performance of spectral scales that rely on chromatic contrast was found poor compared to the grayscale mode[1].

An additional element that motivates this study is the known preference of some radiologists to using tinted bases in radiographic films. Even among currently available monochrome display devices, noticeable variations in the color coordinates of their gray-scale can be seen. It has also been proved that undesired color reflections from ambient luminance can shift the sensitivity of the human observer in a non-reproducible fashion[2].

METHODS

During this study, all aspects of display quality remained unchanged. We used a 1280 x 1024 color active-matrix liquid crystal display to present the image sets to the observers, Fig. 1. Cathode-ray devices, specially designed based on aperture grilles, are not suitable for this study because color can affect the device resolution. We assumed that the variation in display quality parameters in the AM-LCD is minimal within the color space sampled. The luminance range of the display was measured to be about 150, with L_{min} = 0.60 nit and L_{max} = 92.6 nit. Color was generated by preferential filtering of the white light source (back light), Fig. 1.

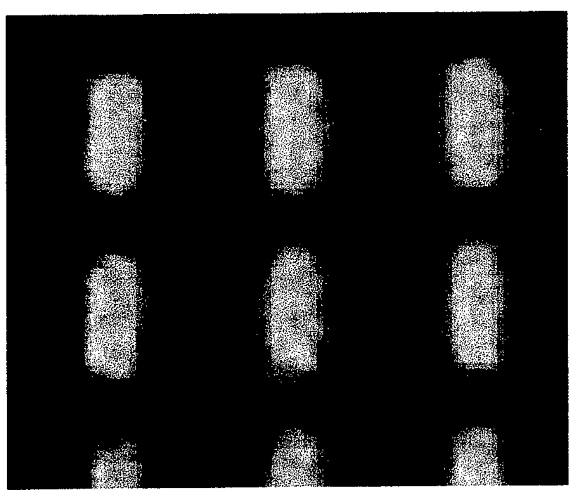


Figure 1. Color in targets generated by preferential filtering of the white light source (color desktop AM-LCD).

The viewing distance between observer and AM-LCD was fixed using marks in the floor for positioning of the chair. We used black panel boards around the AM-LCD to block reflections and to control the stimulation of the observers from regions other than the display. The application menu bars were minimized or hidden when possible. We performed an initial explanation of the experiment and the questions to be answered with each observer for a period of at least 10 minutes (training session). The training and the experiments were performed at low ambient room illumination levels.

We generated low-contrast sinusoidal gratings within circular targets with a diameter of 100 pixels and a frequency of 0.05 lp / pixel (about 0.25 lp / mm) above the visibility threshold for a grayscale mode (see Fig. 2). A mid-gray uniform field of 400 by 400 pixels surrounded the targets. Using an iterative process of adjusting the color and luminance, we modified the targets to obtain a collection of six different colored scales based upon the hue and saturation levels, while maintaining a constant luminance map. The six colored scales and the "white" grayscale constituted the seven colored scales used in the observer study.

Figure 2. Supra-threshold contrast test pattern with sinusoidal grating used in this study. The background field is at an average luminance.

We measured color coordinates and luminance of the patterns for each scale with a CCD spectral analyzer with fiber optic probe, and a photometer, respectively. From the spectra recorded for each pattern, we computed the color coordinates according to the CIE 1931 standard[3], by convolving the measured spectra with the color-matching functions $x(\lambda)$, $y(\lambda)$, and $z(\lambda)$:

$$X = K\int_{380nm}^{780nm} S(\lambda)x(\lambda)d\lambda$$

$$Y = K\int_{380nm}^{780nm} S(\lambda)y(\lambda)d\lambda$$

$$Z = K\int_{380nm}^{780nm} S(\lambda)z(\lambda)d\lambda$$

Where, K is a constant.

The 1931 CIE color coordinates (x,y,z) are obtained by normalizing X, Y, and Z: $x = X/(X+Y+Z)$, and $y = Y/(X+Y+Z)$. We performed independent measurements for both the luminance and the CIE color coordinates with a Minolta CS1000 colorimeter. The variations in color coordinates between the two methods were within 0.005, while the variations in measured luminance remained within 5 %. These measurements confirmed equal luminance maps for all the targets, a crucial assumption in our experimental design. Table 2 shows the CIE coordinates corresponding to the measured spectra for the seven colored scales used in this study. For comparison in Table 1 we showed CIE coordinates for phosphors used in medical type monochrome CRTs.

Table 1. Color coordinates according to the 1931 CIE standard for cathode-ray tube monochrome phosphors used in medical imaging monitors.

Emitter	CIE 1931 coordinates	
	x	y
P45 (single crystal)	0.280	0.304
P104 (blended phosphor)	0.257	0.319

Table 2. Color coordinates according to the 1931 CIE standard for the color scales used in this work. The scale 1 is for unmodified gray level, scales 2, 3 and 4 represent the non-saturated red, green, and blue levels, while scales 5, 6, and 7 are the chromaticity coordinates for the saturated red, green and blue levels.

Scale	Luminance (nit)	CIE 1931 coordinates	
		x	y
1	35.67	0.305	0.327
2	38.10	0.325	0.334
3	35.82	0.315	0.348
4	36.67	0.297	0.323
5	38.23	0.350	0.336
6	36.22	0.320	0.368
7	36.20	0.273	0.307

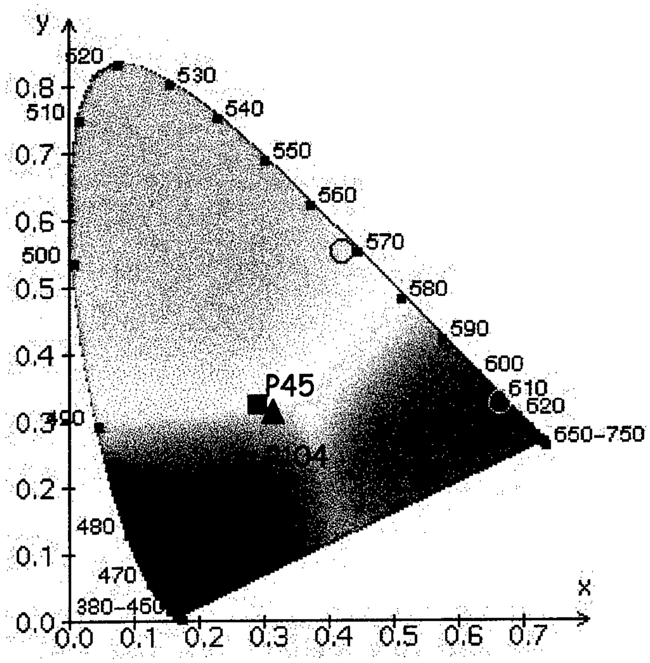
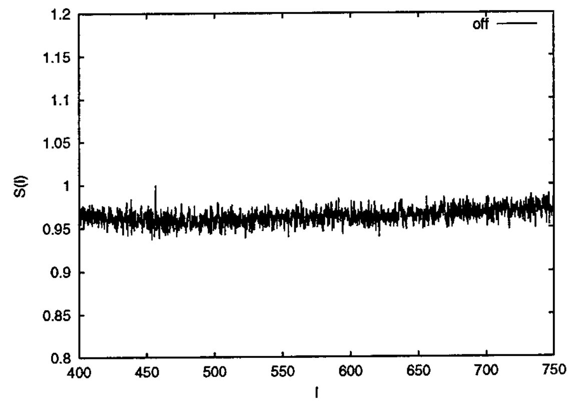
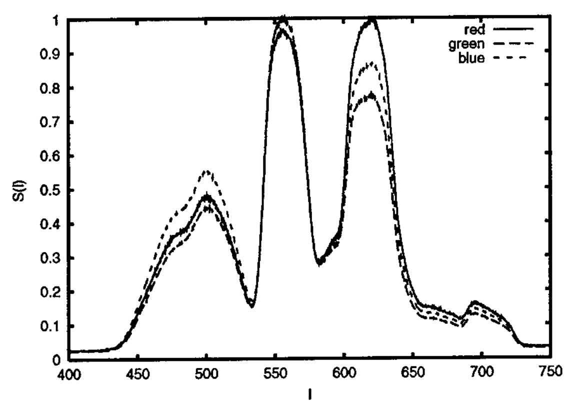


Figure 3. 1931 CIE color coordinates for phosphors used in medical type CRT (■ P45 ▲ P104) described in Table 1.

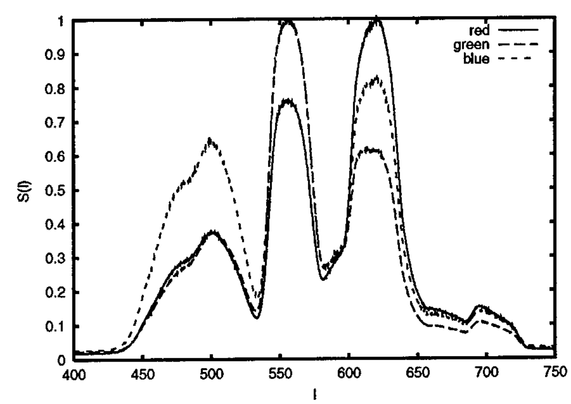
The corresponding spectra to CIE coordinates given in Table 2 recorded from the test patterns used in this work are shown in Fig. 4 (a-b). The contribution from ambient illuminance when the display is turned off is also shown in Fig. 4 (a).



(a)



(b)



(c)

Figure 4. The spectra measured from the test patterns used in this work (a). The contribution from ambient illuminance when the display is turned off. (b) and (c) represents the red, green and blue scales at saturated and non-saturated levels, respectively. S(I)-axis corresponds to the optical signal in arbitrary units and I-axis corresponds to the wavelength in nm.

We performed an initial experiment using a spatial two-alternative forced choice (2AFC) scheme with random presentation of the seven colored scales arranged in pairs. All image targets presented to the viewer contained the same degree of physical contrast. We asked the observers to indicate which of the two targets appeared as having more contrast in the sinusoidal pattern. The experiment consisted of evaluating fifty image pairs. The responses of eighteen observers were compiled using HTMail and analyzed with Perl scripts against the actual order of images. Each observer selected a sequence of image pairs according to the first letter of their computer account identification name.

We analyzed the results by constructing a 7 x 7 matrix P(M,N) where M and N are two of the seven color scales, with the following code: when the perceived contrast of scale A was higher than for B, P(A,B) was increased by unity, and when the perceived contrast of scale B was higher than for A, P(B,A) was increased by unity. When A and B appeared to have the same contrast, no addition was performed. P(M,N) can be interpreted as a map of contrast perception preference, where the combinations of M and N that have the higher values signal that the scale M results in higher perceived contrast than the scale N. If we note that P(M,N) is correlated to P(N,M), we can construct a new matrix P'(M,N) by assigning P'(N,M) = P(N,M)-P(M,N). The final step in the data reduction method is the projection of the half matrix defined by P'(M,N) for $N \leq M$, along the N axis to obtain the function P*(M) that is directly associated with the degree of increased perception of contrast due to the colored scales. When the perceived contrast for a scale S is higher compared to others, we expect P*(S) – avg. (P*) to be positive and significant against the variance of P*.

To evaluate our data processing tools, we generated results for three observers with a priori known response: an ideal observer, a random-response observer, and a blue-biased observer. In Fig. 5, we show the computed P* for these three observers. The ideal observer in this case corresponds to an observer for which the contrast perception response is determined only by luminance contrast and therefore, it is not affected by the color of the scales.

The random-response observer plot shows that if the response of the real observers were to be random, there will be no significant variation in the value of P* across the colored scales. The blue-biased observer is one that always perceives more contrast in patterns using blue scales. The results showed in Fig. 5 confirm that the data processing is correct, and that a difference in the perception of contrast for the color scales can be measured with this scheme.

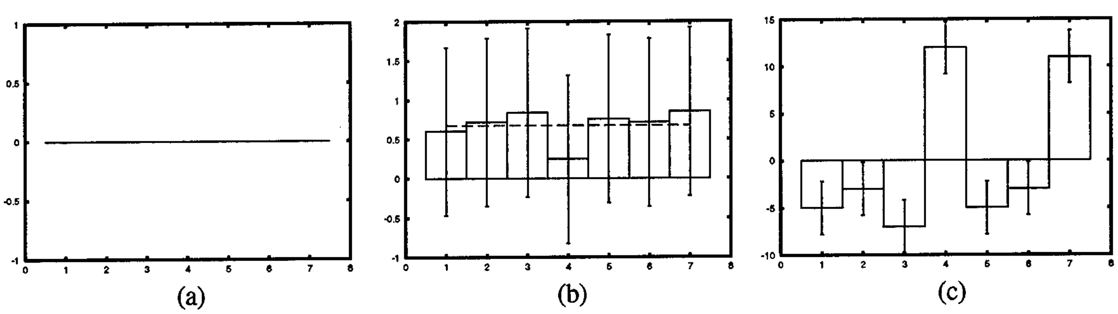


Figure 5. Preference function P* versus scales for three observers with known response: (a) ideal observer, (b) random-response observer, (c) blue-biased observer.

RESULTS AND DISCUSSION

Fig. 6 shows the average response P* for all observers. The error bars at each point represent one standard deviation of the distribution of values of P* among observers. The results suggest that the grayscale is perceived as having less contrast than most of the color scales. Among the color scales, the saturated blue and green appear to convey more contrast than the red and non-saturated scales.

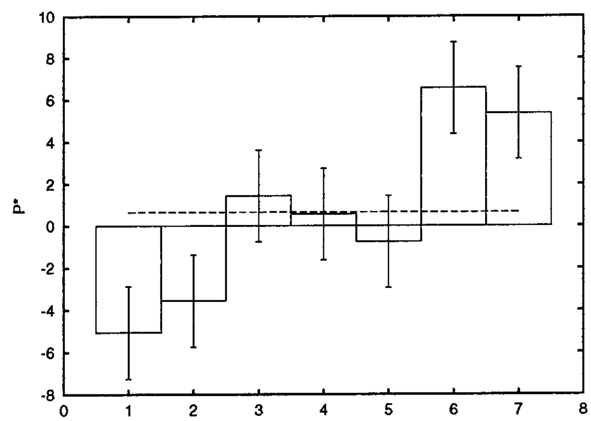
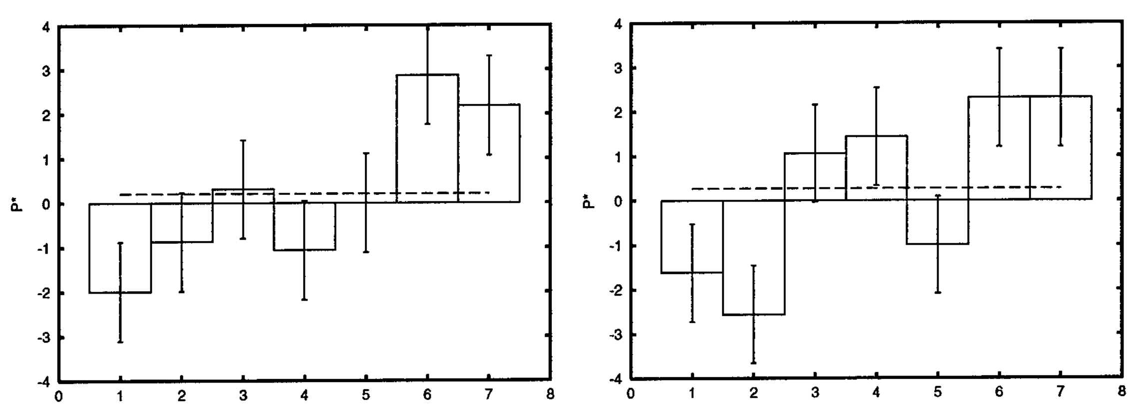
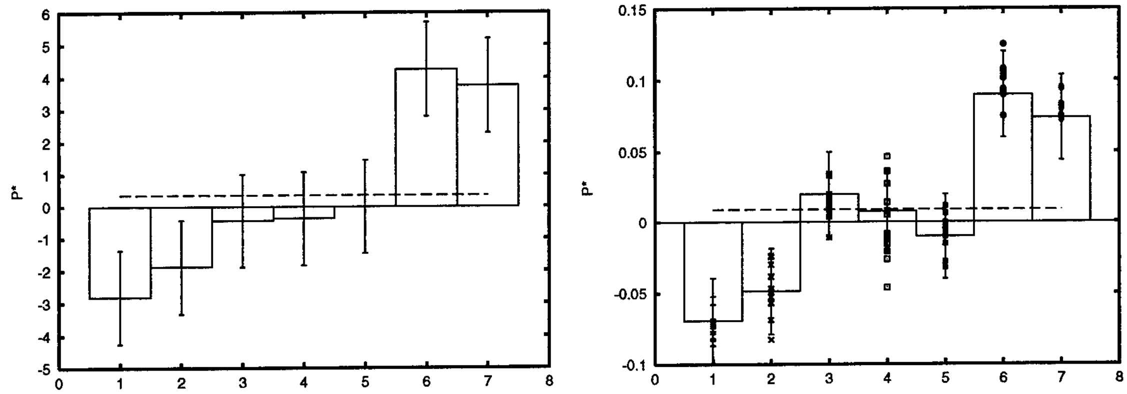


Figure 6. Response P* versus scales for all observers with *llag* = 0 and *flag* = 0. The dashed line represents the average of P* across the color scales.

To understand the robustness of the experiment, we tested for possible learning or fatigue effects. We computed different responses P* according to the described method, but disregarding the first n image pair decisions (*llag* = n), and the last m pairs (*flag* = m). The lag parameters llag and flag stand for "learning" lag and "fatigue" lag. For these cases, the computation of P* is performed with only 50-llag-flag observations. Fig. 7 present the computed P* for several combinations of llag and flag. We noted that there existed a large inter-observer variability that can be attributed to varying personal sensitivities or to prior imaging experience.



(a) (b)



(c) (d)

Figure 7. Effect of the learning and fatigue lags on the response P* is shown. The P* versus scales (a) corresponds to *llag* = 30 and *flag* = 0, (b) corresponds to *llag* = 0 and *flag* = 30, (c) corresponds to *llag* = 10 and *flag* = 10, and (d) shows the results for all the combinations of lags computed.

In Fig. 8, we show the response P* obtained by averaging the fifty image pairs across all observers, along with the individual scores. In particular, we observe that only for two observers, the perceived contrast with grayscale presentation almost equals the perception with the green or blue saturated scales.

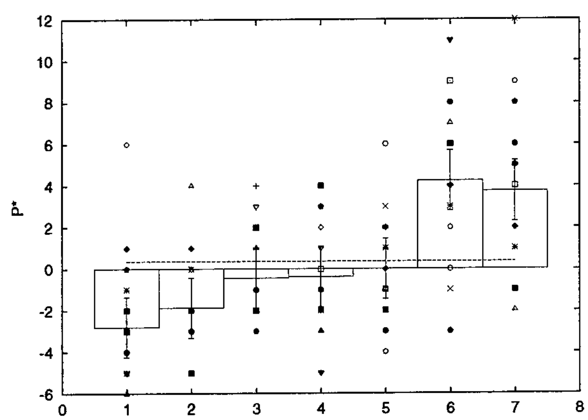


Figure 8. Response P* versus scale for all observers with *llag* = 0 and *flag* = 0. The solid line represents the average of all P*.

CONCLUSION

If it is indeed luminance discrimination that predominantly determines contrast perception, then we would expect no significant shift of the perceptual behavior due to variations in color. The results indicate that the perceived contrast of targets having the same physical contrast in a monochromatic mode varies with color.

Blue and green scales result in higher perceived contrast above the threshold. In addition, observers prefer more saturated green and blue scales (within the gamut used in the study). Grayscale is only almost equally preferred for a small fraction of the observers. The large inter-observer variability suggests that individual factors such as training, preference, color sensitivity and experience may play a role in the mechanism of contrast perception. Although this variability was detected, the results from the study are significant for the average observer.

To our knowledge, ours is the first study to address the effect of a colored grayscale on the detectability of signals and on contrast perception. Because the experiments used backgrounds of the same color as the targets, it is not clear if chromatic adaptation of fovea and periphery affects the outcome. Further experiments should address the effect of chromatic and luminance adaptation using combinations of target and backgrounds of different color.

In phase II of this project we investigated the contrast threshold variations for five color scales (levels).

Phase II. OPTIMAL COLOR FOR SUPRA-THRESHOLD AND THRESHOLD CONTRAST PERCEPTION

RATIONALE

A previous study (Phase I) concluded that the perception of supra-threshold contrast was superior for monochromatic scales in the blue-green region of the spectrum. In this study, we investigate the effect of the monochrome color scale on contrast sensitivity. We used an alternative method to validate those observations. An analysis of the variations in the contrast threshold for five color scales was performed. We used the same targets (same physical contrast with 0.25 line-pair / mm) at the same luminance for all five scales. The targets were surrounded by uniform backgrounds (10 cm x 10 cm) at approximate the average luminance and color coordinates of the sinusoidal circular pattern having a diameter of 100 pixels (about 2 cm). We computed the differences in contrast threshold by fitting a psychometric function to data obtained with eight observers, and by calculating the contrast with a detection probability of 0.5. We find that the contrast threshold for the green scales is in average 20% smaller than ones for the rest of the scales.

METHODS

In the previous experiment (Phase I), the six colors were chosen to cover a broad range of the color scale. Out of the six scales, blue and green scales result in higher perceived contrast above the threshold. Based on the previous findings, five colors were selected including blue and green in unsaturated and saturated versions, plus the grayscale for comparison, in this contrast threshold experiment. Equal physical contrast and equal mean luminance (iso-luminance) patterns across the five scales were generated having 0.25 lp / mm (3 cycles / degree) with sinusoidal modulation near the visibility threshold for a grayscale mode. An example of iso-luminance pattern in one color scale, saturated blue, is shown in the Fig. 9.

We measured color coordinates and luminance of the patterns for each scale with a CCD spectral analyzer with fiber optic probe and a photometer (Minolta CS 100), respectively. The same methods were used in the previous experiment. From the spectra recorded for each scale, we computed the color coordinates according to the CIE 1931 standard. We performed independent measurements for both the luminance and the CIE color coordinates with a Minolta CS1000 colorimeter. The variations in color coordinates between the two methods were within 0.005, while the variations in measured luminance remained within 5 %. Table 3 shows the CIE coordinates corresponding to the measured spectra for the five colored scales used in this study. XX represents grayscale, and BX, GX, BB, GG do unsaturated blue and green, saturated blue and green, respectively. The color maps of the five colored scales are shown in the Fig. 10.

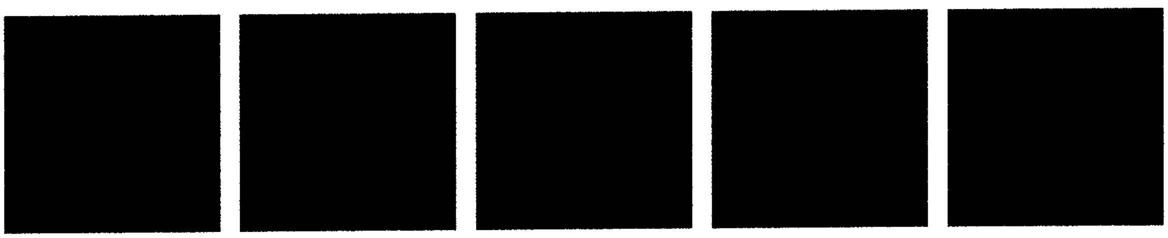


Figure 9. An example of iso-luminance pattern in one color scale, saturated blue, is shown.

Table 3. Color coordinates according to the 1931 CIE standard for the color scales (levels) used in this work. The luminance of the patterns for each scale is also given.

Colored scale	L (nit)	x,y (CIE 1931)
XX	30.1	0.305, 0.327
BX	31.1	0.297, 0.323
GX	30.9	0.315, 0.348
BB	30.2	0.273, 0.307
GG	31.3	0.320, 0.368

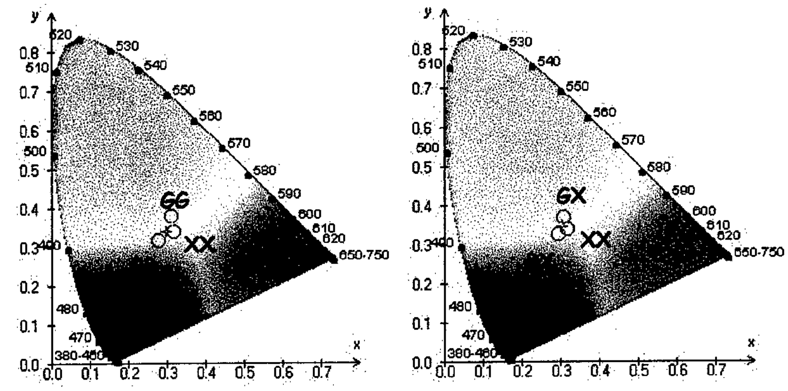


Figure 10. The CIE 1931 coordinates corresponding to the 5 colored scales (XX-gray scale, BX-unsaturated bleu, GX-unsaturated green, BB-saturated blue, and GG-saturated green) used in this work.

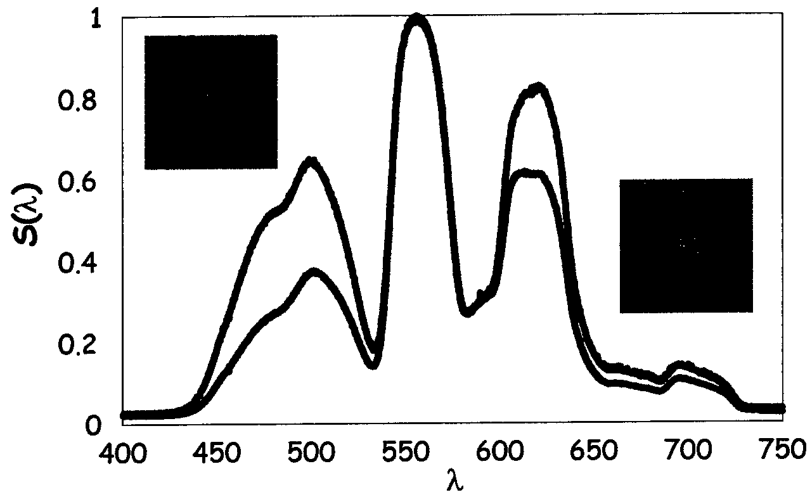


Figure 11. Measured spectral output of two patterns for GG and BB scales using a CCD spectral analyzer with fiber optic probe. The S-axis corresponds to the optical signal and λ-axis corresponds to the wavelength in nm.

A spatial 2AFC was used for patterns with and without target at the center. The target is a sinusoidal circular pattern with 0.25 line-pair / mm having a diameter of 100 pixels (about 2 cm). The contrast of target varies over 10 discrete levels. No additional noise was introduced, thus only display noise and vision noise were present. The background used was 400 x 400 pixels (10 cm x10 cm) at average luminance level. The experiment consisted of evaluating one hundred image pairs per scale, making the total of five hundred image pairs. The responses of eight observers were compiled in this work.

Throughout this study, all the conditions and cautions for the experiment have been kept the same as previous experiment (Phase I). All aspects of display quality remained unchanged. We used a 1280 x 1024 color active-matrix liquid crystal display to present the image sets to the observers. The viewing distance was 70 cm with the subject's position fixed using marks in the floor for positioning of the chair. We used black panel boards on the table and walls behind the AM-LCD to block reflections and to control the stimulation of the observers from regions other than the display. The application menu bars were hidden. We performed an initial explanation of the experiment and the questions to be answered with each observer for a period of at least 10 minutes. The training and the experiment were performed at low ambient illumination levels.

The psychometric curve to be used in this work is generated by plotting the probability of detection for incremental contrast for each color scale. It goes from 0 to 1 as the contrast increases from 0 to 1. The 'a' and 'b' are just fitting parameters of the psychometric model used for P(c) (the probability of detection of pattern with a target having contrast c):

$$P(c) = \frac{10^{ac}}{10^{ac} + b},$$

where a and b are fitting parameters, and c the contrast, respectively[4].

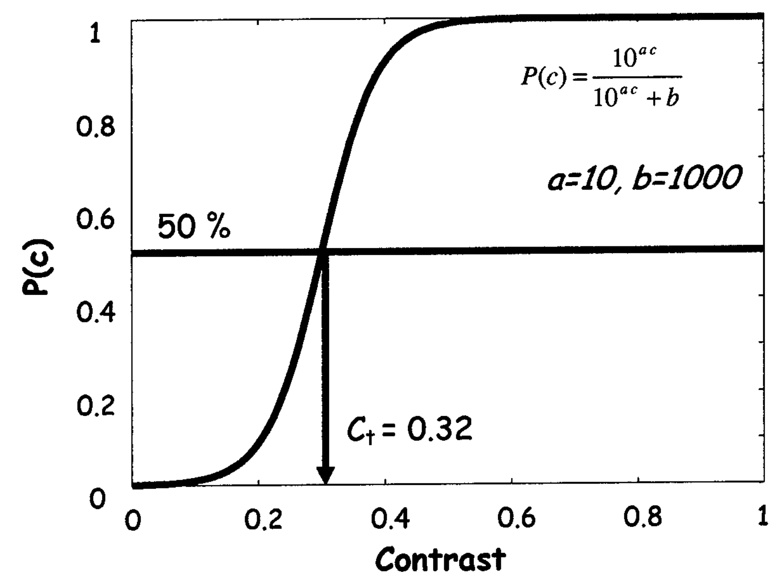
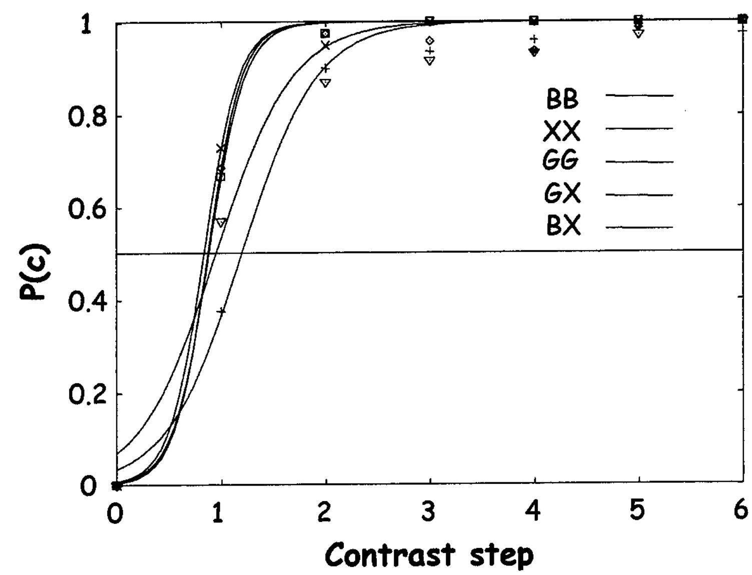


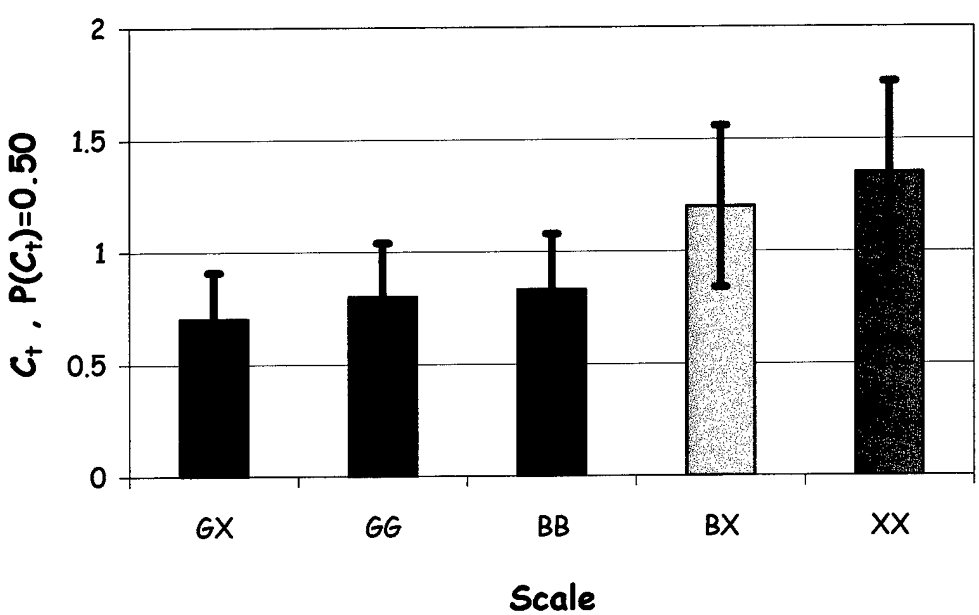
Figure 12. An example of the psychometric curve.

As in the analysis of the previous experimental results, the detection probability was computed as the fraction of true positive cases. Then, we averaged the data points across subjects (8 in this case), and fitted a psychometric curve of the form to the averaged values (see Fig. 12). It is known that the detection of low contrast stimuli should follow a psychometric curve profile. In our case the stimuli are the patterns with or without targets and the response was the processed data interpreted as fraction of true positive cases (i.e., number of times the contrast pattern was detected over total times it was presented). We have computed the probability for 50 and 85 % correct based on the total number of presentation, Figs. 13 and 14.

The 50 % of the probability of detection represents a threshold contrast. In this case larger contrast would have more than 50 % chance of being detected. The minimum contrast threshold was 0.7 for unsaturated green, BX. Saturated blue and green, BB and GG, showed similar contrast threshold of 0.8 and 0.83. Overall, all four colored scales were detected more easily by the observers than the grayscale (XX). The experimental results are shown in Fig. 13



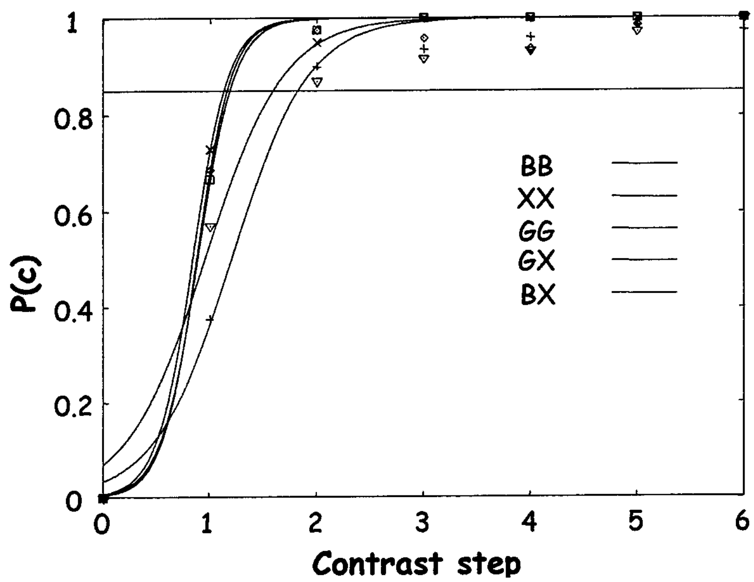
(a)



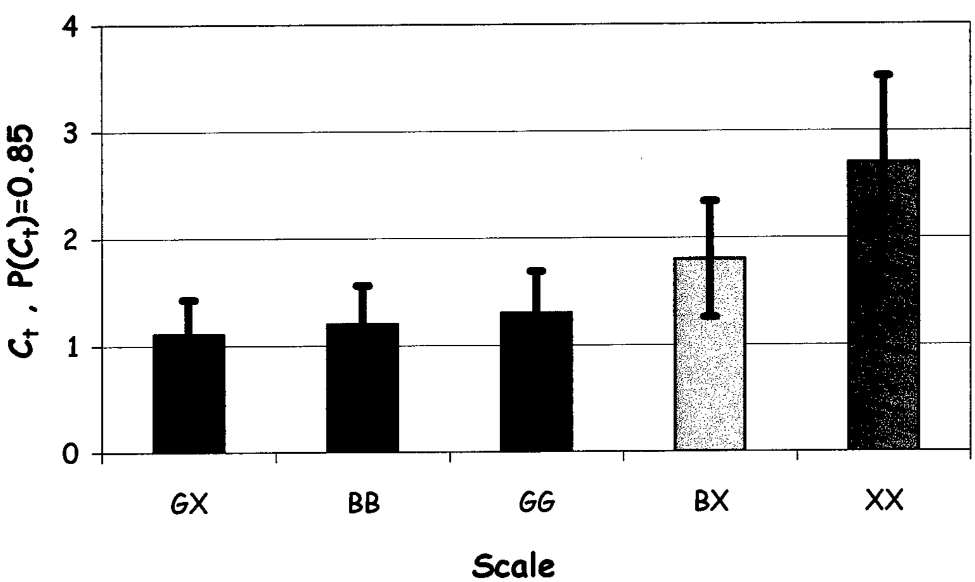
(b)

Figure 13. (a) A psychometric curve and (b) the average contrast threshold computed as the intercept of the psychometric function with the 50 % probability of detection.

On the contrary, the 85 % of the probability of detection represents a typical value used in vision research for detection. It is somewhat arbitrary and there have been other values such as 82, 90, and 95 % used by others. Similar results to the case of the 50 % of the probability of detection have been obtained; and GX showed the minimum contrast threshold of 1.1. Overall trend for all experimental results is similar with the contrast threshold increasing from GX to BX and XX. The experimental results are shown in Fig. 14



(a)



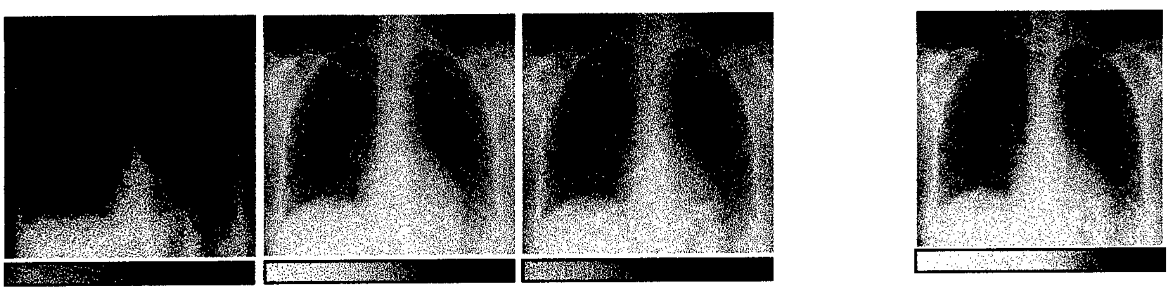
(b)

Figure 14. (a) A psychometric curve and (b) the average contrast threshold computed as the intercept of the psychometric function with the 85 % probability of detection.

The error bars in the contrast threshold plots correspond to the variability introduced by the 8 subjects computed by the standard deviation of the individual psychometric curves to the average data.

RESULTS AND DISCUSSION

In the phase II of this project, the contrast threshold was computed as the intercept of the psychometric function with the 50 or 85 % probability of detection. The colored scales used for this experiment are statistically easier to be detected than grayscale. The three colored scales, GX, GG, and BB, had smaller contrast thresholds over the grayscale as shown in Figs. 13 and 14. Both plots depict the contrast thresholds for five scales. Independent of the definition of threshold, 50 or 85%, the trends are very similar, given the error bars. From these results we can conclude that color scales with lower contrast threshold are better for the particular tasks such as interpretation of diagnostic grayscale images in the medical application, Fig. 15.



(a) (b)

Figure 15. (a) Luminance contrast (with different color at maximum luminance level) and (b) grey scale contrast images

CONCLUSION

We conclude that the contrast threshold for the BB, GG, and GX scales is lower than that for BX and XX (at this particular spatial frequency and observation conditions). The best results were obtained for GX case. The results of this study are consistent with our initial study. Moreover, with this method we could get an estimate of the inter-observer variability.

Future work should include the study of different spatial frequencies using adaptive methods. Also the color-coding schemes, available to user on-demand, should be developed. We were not able to develop and implement these schemes during this project.

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